TRANSFER LENGTH OF HIGH-STRENGTH DUPLEX STAINLESS STEEL STRAND IN PRESTRESSED CONCRETE PILES

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ABSTRACT

With increasing demand for bridge service lives of 100 or more years, engineers face a durability challenge regarding bridges in coastal regions, which experience accelerated corrosion. The use of stainless steel for the construction of prestressed concrete piles could become an attractive alternative to increase the corrosion resistance of coastal and marine structures. To assess the performance of prestressed concrete piles using high-strength 2205 duplex stainless steel (SS), three 70-foot piles, with a 16-in. squared section, were constructed with ½-in. diam. 7-wire SS strand, while two piles were constructed using conventional 1080, 7/16-in. diam. steel strand. The transfer lengths were evaluated at different times for both sets of piles including after driving and extracting the piles, and the results were compared to the requirements of AASHTO-LFRD and to ACI 318. After 14 days, the average measured transfer length was 19.60" (36.4 times the diameter) for the 2205 duplex stainless steel and 20.38" (44.6 times the diameter) for the 1080 steel. These values satisfy both AASHTO and ACI-318 requirements. These results suggest that the stainless steel strand can transfer the prestressing force effectively and that the current codes may be used without modifications for design with this new strand material. Additionally, driving the piles to refusal had little effect on the transfer length.

Keywords: stainless steel, prestressed concrete piles, corrosion protection.

INTRODUCTION

Long-term durability of prestressed concrete bridges subjected to seawater environments is particularly challenging to achieve. Piles located in the tidal zone are subjected to significant deterioration due to the formation of an aeration cell between the regions under and above the waterline. Thus, modern requirements for bridge service life beyond 100 years[1] present a challenge in providing for safe and durable bridges.

Kurtis et al., 2013[2] calculated the diffusion coefficient of several high-performance concrete (HPC) mixtures using results from the Rapid Chloride Permeability Test (RCPT, ASTM C1202/AASHTO T277) and surface resistivity. With these data, they estimated the predicted service life of concrete structures with low (urban environment) and high chloride exposure (marine environment), using Life 365 software. The predicted service life of structures with high chloride exposure ranged between 21% and 31% of that for the low-chloride exposure.

In order to develop an effective way to provide corrosion resistance of structures exposed to marine environments, the use of 2205 duplex stainless steel strands for prestressed concrete piles has been proposed. Stainless steel has been used in reinforced concrete structures due to its enhanced corrosion resistance, even under extremely demanding environments[3]. However, different stainless steel alloy compositions have a wide range of mechanical properties and corrosion performance.

Moser, 2011[3] studied several stainless steel alloys to determine the more suitable to be used for high-strength prestressing strands for prestressed concrete piles. After this investigation, the duplex 2205 stainless steel alloy was chosen as the most promising alloy. The 2205 duplex stainless steel microstructure is composed of ferrite and austenitic phases, which provide a superior corrosion resistance compared to AISI types 304, 316, and 317 austenitic stainless steels after those alloys have been strain hardened to produce high-strength wire[3,4]. Schuetz, et al. (2012)[5] showed that the tensile strength of the 7-wire strand made with the 2205 alloy had tensile strength of about 241.5 ksi and that stress relaxation was less than 2.5% after the strand was subjected to an induction heating process.

However, the details of the behavior of piles reinforced with this new prestressing strand need to be determined before it can be used for design. The research presented in this article compares the transfer length of prestressed concrete piles using the 2205 stainless steel strand with that of conventional strand to determine if specifications given in both ACI 318[6] and AASHTO[7] may be safely used for design with the stainless steel strand.

According to ACI 318-11[6], the transfer length (l_t) is the "length of embedded pretensioned strand required to transfer the effective prestress to the concrete". The effective prestress is the stress in the strands after accounting for losses. The ACI 318-11 code provides that the transfer length can be calculated using Eq. 1.

$$l_t = \frac{f_{se}}{3000} d_b \quad (1)$$

where d_b is the diameter of the prestressing strand(in.), and f_{se} is the effective prestress in the prestressing steel (psi).

The AASHTO LRFD specification, 2013 Interim Revisions[7], suggests that the transfer length should be taken as 60 strand diameters ($60 \times d_b$).

METHODOLOGY

DESIGN OF PRESTRESSED CONCRETE PILES

Five 70-ft long, 16-in. square precast prestressed concrete piles were fabricated at Standard Concrete Products Company, Savannah, Georgia. Each pile was reinforced with 12 strands with a 3 in. cover and with W3.4 wire spiral reinforcement. Two piles were fabricated with conventional 7/16–in. diam. 1080 strands and stressed to 70% of the ultimate strength (189 ksi). Simultaneously, three piles were fabricated using ½-in. diam. 2205 stainless steel strands along with grade 304 stainless steel wire spirals (see Fig. 1). The 2205 strands were stressed using the same total prestressing force as used in the 1080 piles. All piles were stressed from one-end, the south end. Construction for the piles with stainless steel reinforcement was completed with the same operations as for the conventionally reinforced piles. No difficulties were encountered when using the stainless steel strand and wire; no special operations were required (see Fig. 2).

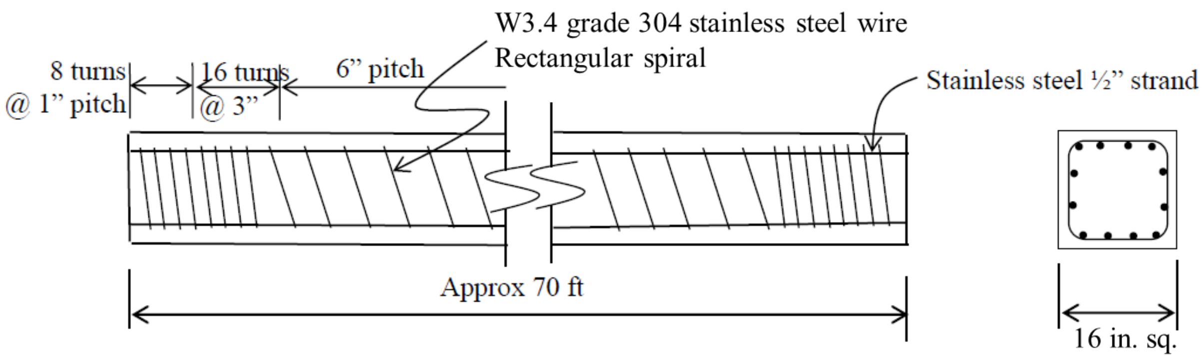

Fig. 1. Typical 2205 stainless steel test pile.

(a) (b)

Fig. 2. Pile fabrication, (a) 1080 conventional steel strands on left, and 2205 stainless steel strands on right, (b) concrete placement operation. Piles were instrumented with vibrating wire strain gauges (red lead wire).

PROPERTIES OF 2205 DUPLEX STAINLESS STEEL

Low relaxation 2205 duplex stainless steel strands were produced under the same conditions as conventional 1080 steel, at Sumiden Wire Products Corporation in Dickson, TN. The ½-in. 7-wire prestressing strand was subjected to stress relaxation process of 716°F (380 °C) and a pull force of 40% UTS. The estimated cost of 2205 SS strand is 6 to 8 times the cost of conventional steel strand.

The mechanical properties of 2205 SS and 1080 steels are shown in Table 1. A detailed study of the mechanical properties of 2205 SS strands was developed by Schuetz et al. (2013)[5]. The 2205 SS had about an 11% lower strength than conventional 1080 strand. To account for this factor, a larger diameter (½-in. compared to 7/16-in.) was used for the 2205 SS strands.

Table 1. Mechanical properties of strands (standard deviation shown in parenthesis).

Alloy	f_y, 0.2% offset (ksi)	UTS (ksi)	Ultimate Strain (%)	Elastic Modulus (ksi)
1080 Conventional	254.7 (0.64)	281.8 (2.00)	5.89 (0.59)	29,400 (130)
2205 Duplex SS	228.7 (2.35)	241.5 (0.07)	1.60 (0.07)	23,500 (190)

Electrochemical cyclic potentiodynamic polarization tests (ASTM G61[8]) were performed by Moser, 2011[3], to evaluate the corrosion resistance of both types of steel alloys under alkaline (pH ~12.5) and carbonated (pH ~ 9.5) solutions with variable chloride concentrations (0 to 1.00 M, where 0.5 M could be considered seawater concentration). While 2205 SS showed no evidence of pitting or corrosion initiation under any of these conditions, conventional 1080 evidenced extensive corrosion damage on every condition, but the alkaline solution with no chloride ions present, which could be considered the common initial internal environment of the reinforced concrete.

PROPERTIES OF CONCRETE

The design strength of the concrete (f_c') was 5,000 psi. Concrete was produced at the plant, and nine batches were necessary to build the piles and smaller specimens for strength and durability testing. The average of three 4x8-in cylinders was used to determine the compressive strengths at 1, 4, 7, 28, 91, and 243 days. Table 2 gives the average strengths at 28-days while Fig. 3 gives the strength gain curve over time. The strength at release was 4,020 psi. All cylinders were kept in moist curing conditions until the time of tests to mimic the submerged condition of the piles.

Concrete mixture had a water to cementitious material ratio (w/cm) of 0.33, Type I Portland cement (OPC), 17% fly ash by weight replacement of OPC, coarse aggregate size #67 (MSA = ¾”), and retarder, high-range water reducer and air entrainment admixtures.

Table 2. Variability of concrete assessed by the 28-day compressive strength.

Pile Denomination	Mean Compressive Strength at 28 days (psi)	Standard Deviation (psi)
Pile 1 - 1080 Conventional	8,800	101
Pile 2 - 1080 Conventional	6,760	500
Pile SS 1 - 2205 Stainless Steel	7,800	500
Pile SS 2 - 2205 Stainless Steel	7,910	398
Pile SS 3 - 2205 Stainless Steel	8,140	33

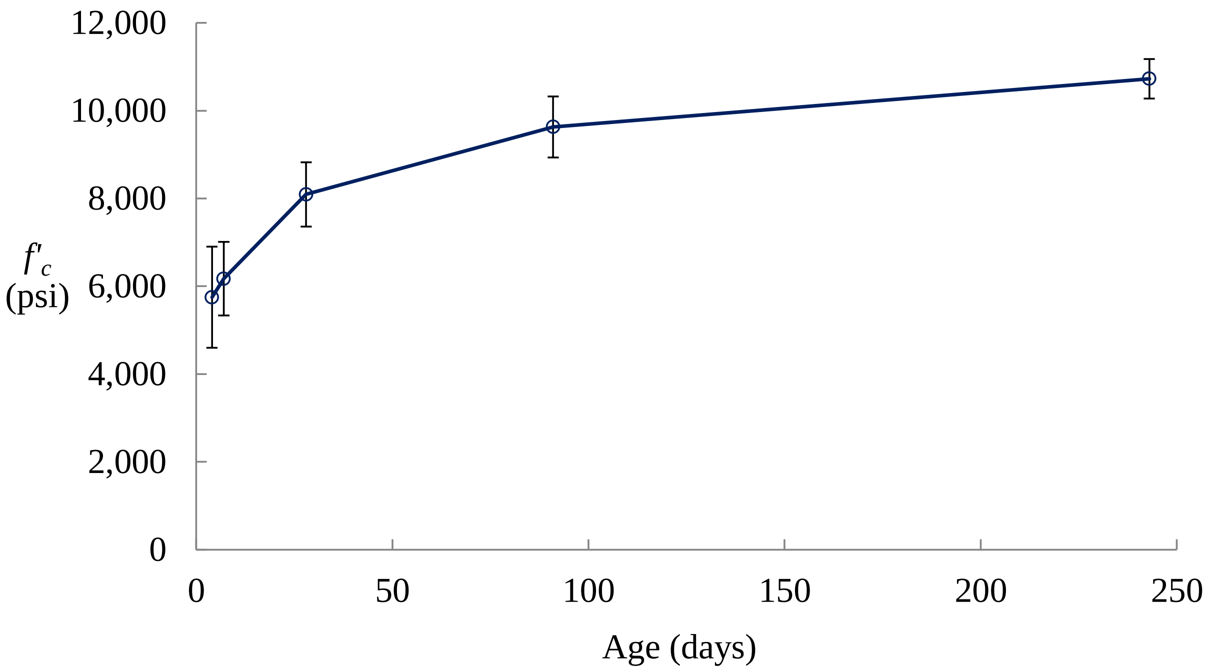

Fig. 3. Average concrete compressive strength at 4, 7, 28, 91, and 243 days. Error bars show standard deviation.

DRIVING OF PILES

Six months following the pile construction, the five piles were driven to refusal in the Savannah River using a D-30 hammer on setting #3 (Fig. 4.a). Table 3 shows the pile resistance capacities for each pile. All five piles exceeded the design capacity of 82 tons. The stainless steel reinforced piles performed similarly to the conventional strand piles. The piles were extracted for future flexural, shear, and development length tests (Fig. 4.b). No cracking, spalling or other damage was noted in any pile.

Table 3. Summary of pile driving results for both conventional stranded piles and stainless steel reinforced piles.

Pile Denomination	Travel for 10 Blows (in.)	Bearing Capacity (tons)
Pile 1 - 1080 Conventional	1.75	97
Pile 2 - 1080 Conventional	1.25	112
Pile SS 1 - 2205 Stainless Steel	1.5	104
Pile SS 2 - 2205 Stainless Steel	1.5	104
Pile SS 3 - 2205 Stainless Steel	1.5	104

(a) (b)

Fig. 4. (a) Driving operation of piles, (b) Extraction of piles through water jet stream applied at the bottom of the pile.

DESCRIPTION OF TRANSFER LENGTH TESTING METHOD

The concrete surface strain (CSS) and the 95% average maximum strain method (95% AMS), discussed by Russell[9], was used to determine the transfer length. DEMEC gauge points were embedded in the top surface of the pile ends directly above both vertical rows of strands by suspending them with steel plates and wooden braces as shown in Fig. 5.a. The DEMEC points were spaced at 2-in. intervals over 8 ft. at each end of each pile. CSS measurements were taken on before release of the strands (Fig. 5.b), immediately after release, at 1 day, 14 days, and after driving the piles (273 days). Measurements were made before sunrise to minimize the variability due to temperature gradient, and an INVAR bar was used as a reference to account for the temperature variation within measurements performed on different days. The precision of the DEMEC tool used was 0.0001 in. and 86 measurements were made per each pile end.

(a) (b)

Fig. 5. (a) Embedded elements left uniformly spaced points to be measured with a DEMEC gauge, (b) Measurement of deformations at the surface of the piles. 86 measurements were made at each pile end.

RESULTS

Fig. 6 shows typical smoothed CSS data plotted for specimen 2205-1 North at 14 days. The strain measurements begin from the end of the pile, and initially, the data have a linear increasing slope until it levels off into a continuous plateau. Using the 95% AMS method, the transfer length is the distance from the end of the pile until the intersection of the increasing linear trend-line and the 95% AMS line. The surface strains from each pile end resemble those in Fig 6, and all of the transfer length results are listed in Table 4.

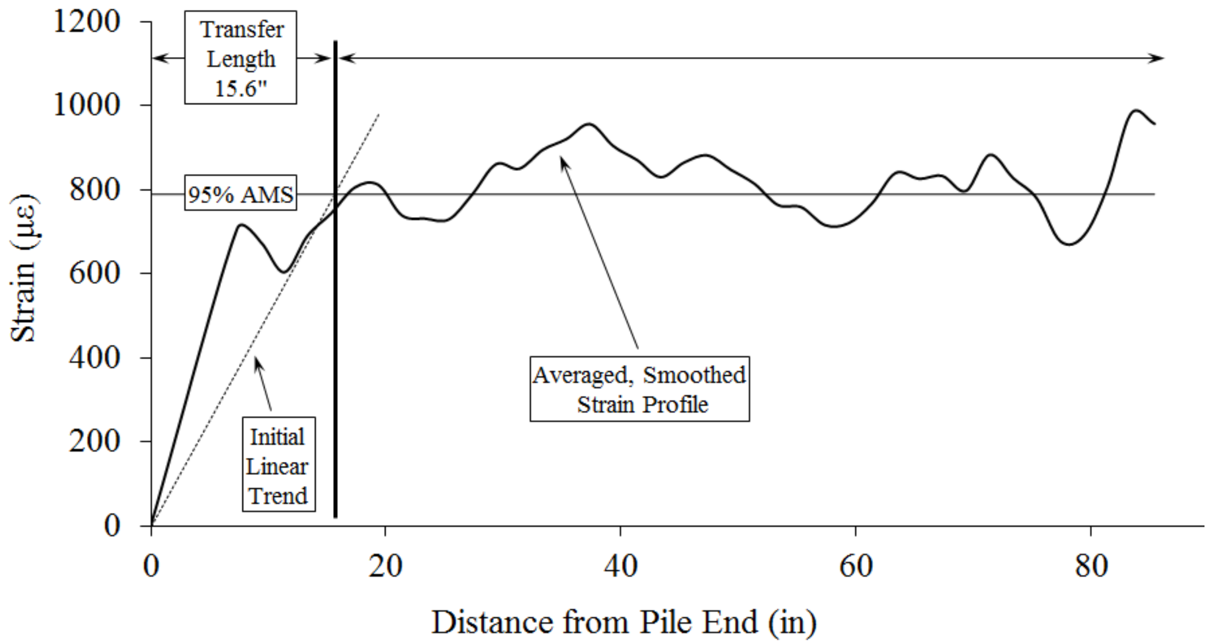

Fig. 6. Transfer length plot for pile SS 2205 #1 – North End, 14 days after prestressing.

Table 4. Summary of transfer length results at day 14 and after driving (comparison to AASHTO in parenthesis). Results are compared with values required by AASHTO LFRD[7] and ACI 318-11[6].

Pile	**1080-1**		**1080-2**		**2205-1**		**2205-2***		**2205-3**	
End	South	North	South	North	South	North	South	North	South	North
Day 14	**9.9”** (38%)	**22.2”** (85%)	**13.4”** (51%)	**25.5”** (97%)	**9.8”** (33%)	**15.6”** (52%)	**17.3”** (58%)	**24.7”** (82%)	**13.6”** (45%)	**21.7”** (72%)
Average (day 14)	**17.8”** (68%)				**17.1”** (57%)					
Day 273 (after driving)	**10.0”** (38%)	**22.0”** (84%)	**12.3”** (47%)	**16.4”** (62%)	**10.3”** (34%)	**11.5”** (38%)	**23.7”** (79%)	**24.0”** (80%)	**13.3”** (44%)	**20.9”** (70%)
Average (day 273)	**15.2”** (58%)				**17.3”** (58%)					
AASHTO LRFD - 12	26.25”				30.00”					
ACI 318-11	26.81”				22.96”					

*required additional mechanical work to remove from form bed during fabrication.

Comparing the behavior of the jacking end (south) versus the anchorage end (north), all of the piles behaved similarly. Every pile had a larger transfer length on the anchorage end of the pile than on the jacking end; the anchorage end had approximately 100 ft. of free strand compared to about 10 ft at the jacking end.

Pile driving had little effect on the transfer length. Fig. 7 compares the transfer length at 14 days versus that after driving for pile 2205-1; Fig. 7 is typical of the measurements. While, most of the piles sustained an increase in overall compressive strain, the transfer length remained the same. Seven of the ten pile ends had a decrease in transfer length after driving.

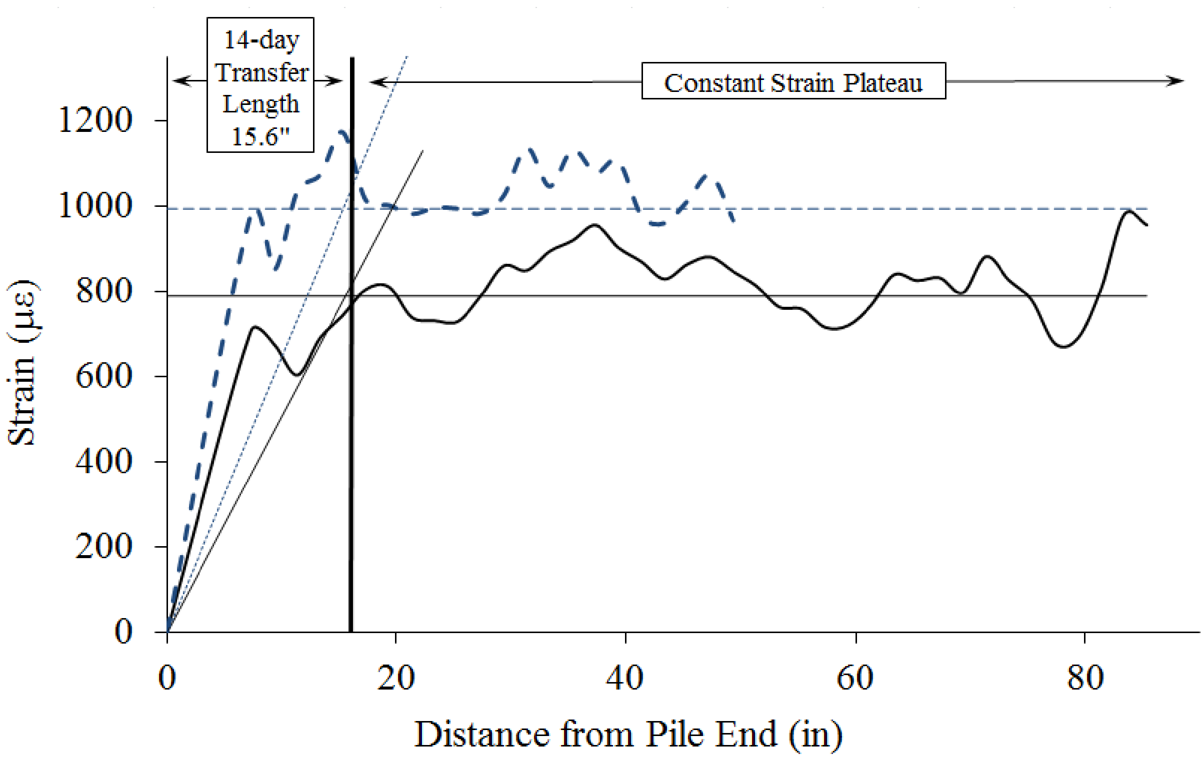

Fig. 7. Comparison of transfer length calculation for pile SS 2205 #1 – North End, after 14 days (black line) and after driving process (day 273, dashed blue line).

If the measured transfer length was less than the code calculated distance, then the code equation was considered conservative. All of the transfer lengths measured for both the conventional and stainless steel strand were less than the AASHTO calculated distances as given in Table 4. Thus, the AASHTO specification is conservative for both 1080 and 2205 steel strands. Conversely, the 1080 transfer lengths were less than the ACI equation, but not all of the 2205 lengths were. The average transfer lengths were 66% and 75% of the ACI length for the 1080 and 2205 steel strands respectively. However, pile 2205-2 North was 108% of the ACI value. Pile 2205-2 was not easily removed from the form bed during fabrication and required additional mechanical work. This early disturbance and vibration of the pile could contribute to the relatively higher transfer length values.

CONCLUSIONS

The transfer lengths of 2205 duplex stainless steel prestressing strands was compared to those measured on piles with conventional 1080 steel prestressing strand and to transfer lengths calculated based on ACI 318-11[6] and AASHTO LRFD[7] specifications. The following conclusions were drawn from the experimental research:

- The calculated transfer length of prestressed concrete piles built using 2205 duplex stainless steel showed a similar value compared to conventional 1080 steel.

- The measured transfer lengths at 14-days for 2205 duplex stainless steel strand were 75% and 57% of the lengths calculated based on the requirements of ACI 318-11[6] and AASHTO LRFD[7] codes, respectively.

- The measured transfer length of piles constructed with conventional and stainless steels was little affected by pile driving. The average change in transfer length was a decrease of 3.6%. These conclusions show that the transfer length of 2205 duplex stainless steel prestressing strand may be calculated conservatively with the current methods and that this calculated value may be used to assess the behavior of the pile after driving.

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